Forest Research
Technical Report
Vancouver Forest Region
2100 Labieux Road, Nanaimo, BC, Canada, V9T 6E9, 250-751-7001

TR-012 Geomorphology March 2001

Transport of logging slash and sediment in S5 and S6 streams near Boston Bar, Chilliwack Forest District

by
Thomas Millard, Research Geomorphologist

Research Disciplines: Ecology ~ Geology ~ Geomorphology ~ Hydrology ~ Pedology ~ Silviculture ~ Wildlife

106-05547/

TABLE OF CONTENTS

	Page
Summary	2
Keywords	2
Acknowledgements	2
Regional Contact	2
1 Introduction	2
2 Study Area	4
2.1 Peak Flow Events	4
3 Study Design and Data Collection	6
3.1 Study Design	6
3.2 Data Collection	6
3.2.1 Predictor variables	6
3.2.2 Response variables	7
3.2.3 Informative variables	7
4 Results	7
4.1 Selection of predictor variables for multivariate analysis	11
4.2 Logging slash movement and jam development	12
4.2.1 Size of woody debris moved	12
4.2.2 Average size of debris jams	12
4.2.3 Normalized debris jam volume	12
4.3 Sediment wedge development	13
4.3.1 Average sediment wedge volume	13
4.3.2 Normalized sediment wedge volume	13
4.4 Analysis of overall disturbance	14
5 Discussion	14
6 Conclusions	15
7 References	15

Tables:

1 Water Survey of Canada stations near Anderson R.	5
2 Peak flow records for Nov. 29-30, 1995	5
3 Peak flows for 1997	5
4 Peak flows for 1999	5
5 Comparison of channel width and the size of woody debris moved	12
6 Comparison of sediment size moved and the size of woody debris moved	12
7 Assessment of water transport potential	15
8 Recommended cleaning strategy	15

Figures:

1 Map of study area	3
2 Average gradient	7
3 Stream location	10
4 Terrain/landform types	10
5 Bank types	10
6 Normalized bank erosion	11
7 Average size of woody debris jams vs. channel width	12
8 Effect of width on normalized debris jam volume	12
9 Effect of gradient on normalized debris jam volume	12
10 Effect of width on average sediment wedge volume	13
11 Effect of width on normalized sediment wedge vol.	13
12 CHAID tree for overall disturbances in Anderson River study streams	13

Photos:

1 Stream 12, Reach 4 (no disturbance)	8
2 Stream 17, Reach 1 (extensive disturbance)	8
3 Stream 20, Reach 5 (moderate disturbance)	9
4 Stream 25, Reach 1 (severe disturbance)	9

Cover Photo: Researcher examines logging debris jam on one of the study streams, Anderson River area.

SUMMARY

Under the Forest Practices Code of British Columbia, a forest reserve may not be required alongside S5 and S6 streams. S5 and S6 streams are non-fish streams outside of community watersheds. In S5 and S6 streams that have harvesting adjacent to their banks, deposition of additional quantities of woody debris (logging slash) into the stream may occur. Removal of this logging slash (usually referred to as stream cleaning) is often done to prevent increased transport of woody debris and sediment into fish streams connected to the S5 or S6 stream. This report investigates the transport of logging slash and sediment in "slash-full" streams.

This study is the second phase of a project initiated in 1999 to examine the effects of logging slash in channels, and to provide recommendations to assist in the decision of whether stream cleaning would be beneficial. The first phase of the project examined streams near Nitinat Lake, in southwestern Vancouver Island (Millard, 2000). This second phase of the project examined streams within the Anderson River watershed, on the east side of the Fraser Canyon near Boston Bar.

The project has two objectives:

1. To determine how channels respond if logging slash is left in the stream, and,

2. To identify stream parameters that can be used to predict the likelihood of channel disturbance and downstream transport of logging slash and sediment.

Forty-three stream reaches were surveyed, with the data from 42 streams analysed. Most of the streams were logged from 1986 to 1993, with two additional study reaches logged in 1997. Most of the channels were located in thick, fine-grained till sediments.

The following response variables were measured: size of woody debris transported, the size of woody debris jams that developed in the study reach, the size of sediment wedges that developed in the study reach, and the overall level of disturbance in the channel. Bankfull channel width was shown to be the most significant predictor variable for all of these response variables. The size of sediment transported in the study reach was another significant predictor variable.

Based on the results of this study and Millard (2000), recommendations for stream cleaning of S5 and S6 streams were developed.

KEYWORDS

channel, stream, disturbance, woody debris, logging slash, Chilliwack Forest District

ACKNOWLEDGEMENTS

I would like to thank David Campbell of JM Ryder and Associates for his contribution of field work and many useful discussions. Reviews of this document were done by Peter Ott, Bruce Thomson, and Scott Babakaiff.

REGIONAL CONTACT

For further information contact: Tom Millard, Research Geomorphologist, Vancouver Forest Region, BCMOF, (250) 751-7115; email tom.millard@gems8.gov.bc.ca. This report is available at the Vancouver Forest Region website: http://www.for.gov.bc.ca/vancouvr/research/research_index.htm

1.0 INTRODUCTION

Small forested channels almost always contain woody debris. Woody debris is introduced to a channel through a variety of processes, including windthrow or windsnap of limbs or whole trees, bank erosion, landslides, and delivery of wood from upstream channel reaches. The effect of woody debris on channel morphology depends on both channel and woody debris characteristics, but in many streams it constitutes an important geomorphic element.

Under the Forest Practices Code of British Columbia, a forest reserve may not be required alongside S5 and S6 streams. S5 and S6 streams are non-fish streams outside of community watersheds. In S5 and S6 streams that have harvesting adjacent to their banks, deposition of additional quantities of woody debris (logging slash) into the stream may occur. Removal of this logging slash (usually referred to as stream cleaning) is often done to prevent increased transport of woody debris and sediment into fish streams connected to the S5 or S6 stream. There may be other reasons for stream cleaning; however only the potential for increased transport of woody debris or sediment out of a specific stream reach is considered in this report.

Underlying this project is the premise that, several years after logging, an uncleaned, slash-full stream will show evidence of how the slash has affected the channel morphology, and will also show whether transport of either logging slash or sediment has occurred. If there is no evidence of logging slash transport within an S5 or S6 stream reach, then no logging slash was transported into downstream fish-bearing reaches. Similarly, if there is no evidence of bed or bank erosion, or development of sediment wedges within an S5 or S6 reach, then the logging slash is not causing increased transport of sediment into downstream fish-bearing reaches.

However, the converse is not necessarily true. Evidence of logging slash transport or sediment transport within an S5 or S6 reach does not always equate with the introduction of these materials into downstream fish bearing reaches. Movement of logging slash or sediment may occur within a reach, but this does not necessarily mean slash or sediment is transported out of the reach. Intermediate reaches between a specific S5 or S6 reach and the fish-bearing reaches will also affect whether sediment or logging slash is delivered to a fish-bearing reach. But although evidence of disturbance within the study reach does not necessarily equate to disturbance in downstream fish-bearing reaches, the recommendations in this report are based on the assumption that within-reach disturbance should be minimised.

This study is the second phase of a project initiated in 1999 to The area has several biogeoclimatic zones (BGC) whose distri-

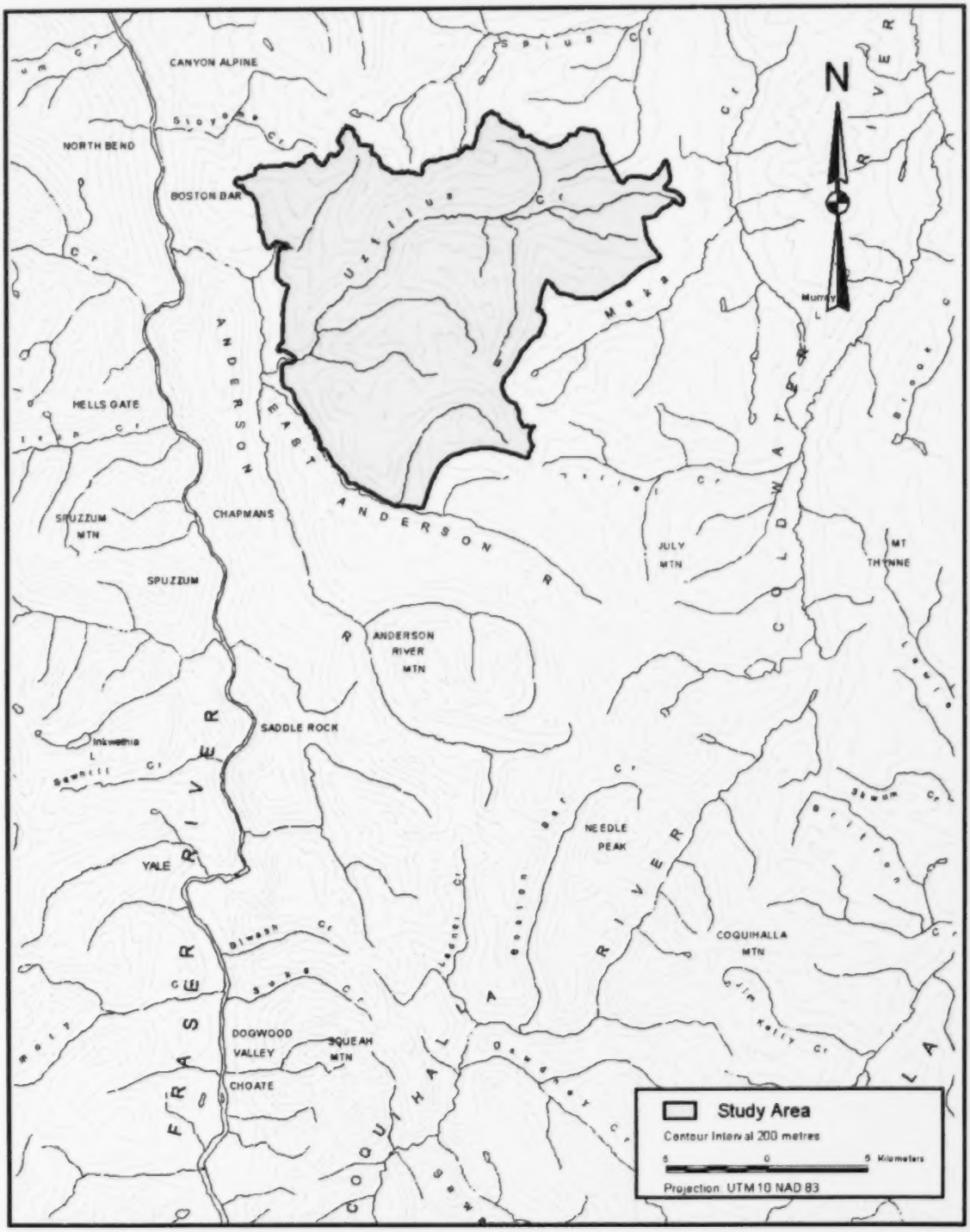


Figure 1: Location map, Anderson River watershed

examine the effects of logging slash in channels, and to provide recommendations to assist in the decision of whether stream cleaning would be beneficial. The first phase of this project examined streams near Nitinat Lake, in the southwest portion of Vancouver Island (Millard, 2000, hereafter referred to as TR-005). This second phase of the project examines streams within the Anderson River watershed, on the east side of the Fraser Canyon near Boston Bar. In this study, the emphasis is on analysing quantitative measures of woody debris and sediment movement, rather than the qualitative analytical emphasized in TR-005. The Anderson River was chosen for the following reasons:

1. Reviewers of TR-005 noted that most study streams were located on coarse-grained surficial materials, and they postulated that the response of streams on finer-grained surficial materials to logging debris might be different. The east side of the Fraser Canyon is known for its fine-grained surficial materials.
2. The Anderson River watershed represents perhaps the greatest divergence from conditions near Nitinat Lake available within the Vancouver Forest Region. Not only are surficial materials different, but peak flow event processes and biogeoclimatic zones are different. If channel and logging slash interactions are similar between the Anderson River area and the Nitinat Lake area, then they are likely to be similar throughout the Vancouver Forest Region.

The project has two objectives:

1. To determine how channels respond if logging slash is left in the stream, and,
2. To identify stream parameters that can be used to predict the likelihood of channel disturbance and downstream transport of logging slash and sediment.

Further background and discussion can be found in TR-005. A useful additional reference, found after completion of TR-005, is Commandeur et al (1996). Commandeur et al. measured sediment budgets of two small streams in the Squamish Forest District. Both streams were logged, leaving no forest reserve. One stream was cleaned of logging slash, and one stream was not cleaned. The uncleaned stream had about double the input of sediment compared to the cleaned stream (14.8 Mg vs. 7.0 Mg), primarily the result of a single road cutslope source adjacent to the uncleaned stream. Yet despite the greater input of sediment, the uncleaned stream recorded a slightly smaller amount of bedload transported out of the study reach (1.32 Mg vs 1.38 Mg). This study confirms other studies that show leaving logging slash in a stream can trap sediment, whereas removing logging slash in a similar stream is likely to result in increased output of sediment from the reach. In streams such as these the retention of slash can reduce the volume of sediment delivered to downstream fish reaches.

2.0 STUDY AREA

All of the study streams are within the Anderson River watershed, part of the Cascade Mountains physiographic region (Figure 1; Holland, 1976). Most of the study streams are within the Uztlius Creek basin, with some streams in smaller unnamed sub-basins to the north of Uztlius Creek, and some in the East Anderson basin. Two bedrock formations are present within the study area. Foliated granodiorite of Jurassic to Lower Cretaceous age is present in the northern and eastern portions of the study area. The Lower Cretaceous Jackass Mountain is in the western portion of the study area, and is composed of sandstone, pelite and conglomerate (Monger, 1969). Most of the study streams ranged in elevation from about 600 m to 1200 m, and the highest elevation within the study area is 1860 m.

Glaciation has strongly affected the Anderson River area. Ibex Peak and adjacent peaks in the south of the Anderson River watershed held alpine glaciers at the beginning of the Fraser Glaciation, but then ice from the Coast Mountains to the west advanced into the Anderson River basin. As the ice advanced up-valley, it blocked drainage and created a sequence of glacially impounded lakes at the snout of the advancing ice. Further advance of the ice incorporated fine textured glaciolacustrine deposits, resulting in a fine-grained till found in much of the area (Waddington, 1995). Till thickness can be many metres in the bottoms of valleys, but generally decreases as elevation increases. Bedrock is exposed in some upper slopes, and colluvial materials are found on some steep slopes or on fans.

bution is strongly affected by elevation. Lower elevation areas contain the Interior Douglas Fir BGC (Warm Wet variant), and the Coastal Western Hemlock BGC (Southern Dry and Southern Moist Submaritime variants). As elevation increases the Engelmann Spruce – Subalpine Fir zone (Moist Warm variant) is dominant (Green and Klinka, 1994).

2.1 PEAK FLOW EVENTS

For the purposes of this project it is useful to have some understanding of the size of peak flow events that have occurred since logging was completed on the study streams. The amounts of logging slash and sediment transported since logging are dependent upon the size of peak flow events that have occurred after logging. If no large peak flows have occurred since logging, then the amount of logging slash and sediment transport may be minimal. However, the same stream may have significant amounts of logging slash and sediment transport if a large peak flow occurs in the near future. Therefore, the size of peak flow events that have occurred since logging can significantly affect the results of this study.

The Anderson River, and all smaller streams within the basin, are ungauged. Table 1 contains records from four Water Survey of Canada (WSC) stations near the Anderson River. Spius Creek drains an adjacent portion of the Cascade Mountains to the north and east of the Anderson watershed, as well as a portion of the Thompson Plateau (Figure 1). Maka Creek is a tributary of Spius Creek, and is included in the area draining to the WSC station. The Coldwater River and the Coquihalla River drain adjacent areas to the southeast of the Anderson River, with the Coldwater River draining to the northeast and the Coquihalla River draining to the southwest. The Nahatlatch River drains a large watershed on the west side of the Fraser Canyon, about 20 km north of the mouth of the Anderson River. Fall storm run-

Table 1. Water Survey of Canada Stations near the Anderson River.

Station Name	Station Number	Basin area (km^2)	Record Period(s)[1]	Years of record	# of years of fall peak flows[2]
Spius Creek near Canford	08LG008	780	1914-1920, 1970-2000	37	4
Coldwater River near Brookmere	08LG048	316	1966-2000	35	6
Coquihalla River below Needle Ck.	08MF062	85.5	1966-1999	29	7
Nahatlatch R. below Tachewana Ck	08MF065	715	1973-1999	22	7

1) Year 2000 data are preliminary.
2) This is the number of years that have the annual maximum daily discharge recorded from September through January.

off events constitute between 10 and 35% of the annual maximums (Table 1). As would be expected, the most interior of these stations (Spius Creek) has fewer fall storm annual peaks than the streams that are either further west or further south.

The adjacent WSC stations indicate the Anderson River watershed is located in a transitional zone between the coast and interior hydrologic zones. Maximum stream discharges are primarily during spring freshets, but some yearly maximum discharges are the result of fall or winter rainstorms that may also generate snowmelt. Most years produce a substantial snowpack at moderate and high elevations. The Great Bear Snow Pillow station is located along the Anderson River – Coquihalla River watershed divide at an elevation of 1660 m. It averages a peak snowpack depth of 470 cm (Hudson, 2000). It is likely that the Anderson River would have about 20% of its annual peak flows derived from fall storm events.

Although examining the WSC stations can provide a broad overview of runoff events in the Anderson watershed, there is a great difference in stream size between the WSC gauged streams and the study streams. The WSC gauged streams have basin sizes ranging from 85 – 780 km^2. In contrast, the study streams have basin sizes that are typically less than 1 km^2. Peak flow events in the study streams may not occur at the same time or with the same intensity as events at the gauged streams. However, if all of the gauged streams have similar responses during specific events, then it is more likely that all the streams in the area are responding in similar fashion.

Three large peak flow events have occurred since 1993 (the last year of logging for any of the study streams). A large storm

Table 2. Peak flow records for November 29-30, 1995.

Station name	Station #	Rank	Return period (yrs)
Coquihalla River below Needle Creek	08MF062	1/29	33
Coldwater River near Brookmere	08LG048	1/35	32
Spius Creek near Canford[1]	08LG008	11/31	3.0
Nahatlatch R. below Tachewana Ck.[2]	08MF065	12/22	2.2

1) Data for years 1914 – 1920 are not included in the return period analysis
2) The November 29-30 event was not the highest annual discharge for the Nahatlatch River in 1995. However, it was the second highest discharge of 1995, and would have ranked 12th had it been the annual maximum.

event November 29-30, 1995 resulted in very large discharges in both the Coquihalla and Coldwater rivers. However, it did not yield as large events in the streams farther north (Table 2). Although this event was the largest measured to date on the Coquihalla and Coldwater Rivers, it does not appear that the event was as large in the north.

Large spring freshets occurred in May 1997 (Table 3). All of the WSC stations indicate a peak flows with a return period of at least 5 years. The streams to the south had peak flows on May 15, and the more northerly streams peaked on May 31. It is reasonable to conclude that streams within the Anderson basin

Table 3. Peak flows for 1997

Station name	Station #	Peak date	Rank	Return period (yrs.)
Coquihalla River below Needle Creek	08MF062	May 15	5/29	9.3
Coldwater River near Brookmere	08LG048	May 15	8/35	5.3
Spius Creek near Canford	08LG008	May 31	3/31	16
Nahatlatch R. below Tachewana Ck.	08MF065	May 31	2/22	8.6

Table 4. Peak flows for 1999

Station name	Station #	Peak date	Rank	Return period (yrs)
Coquihalla River below Needle Creek	08MF062	May 25	4/29	9.4
Coldwater River near Brookmere	08LG048	June 16	7/35	5.4
Spius Creek near Canford	08LG008	May 25	1/31	34
Nahatlatch River below Tachewana Ck	08MF065	June 16	4/22	6.2

likely had peak flows with return periods greater than five years during May 1995.

Spring freshets were large in 1999 (Table 4). Once again, all four stations had a peak flow event with at least a five-year return period in May or June of 1999. Spius Creek, whose headwaters are closest to the study streams, had its largest recorded discharge.

The 1997 and 1999 spring freshets indicate that large peak flows, with at least a five-year return period and perhaps considerably greater, occurred within a widespread area that includes the Anderson River watershed. The discharge records for neighbouring watersheds indicate that the study streams were likely subject to peak flow events of a significant magnitude.

3.0 STUDY DESIGN AND DATA COLLECTION

The study design and stream characteristics measured were very similar to those followed in TR-005. Where portions of Section 3.0 in this report are in italics, it indicates a different procedure or measurement than that followed in TR-005. The changes are usually refinements of the procedures used in TR-005, or else reflect local conditions that were present in the Anderson River study area but not the Nitinat Lake study area.

3.1 STUDY DESIGN

Streams selected for the study met the following criteria:

- *Logging occurred between about 1985 and 1993.* This allowed time for the stream to respond to several high water events.
- Logging slash had not been removed from the stream.
- The stream was less than 5 m wide. This upper limit was chosen because it seemed evident that if logging slash was retained in streams larger than this, there was significant transport of woody debris.
- There was relatively easy access to the stream, and usually there were a number of suitable streams close to one another.

A stream reach was defined on the basis of general uniformity of channel gradient, bed and bank materials, amount and distribution of logging debris, and volume of flow. If a significant change in any of these attributes occurred, a new stream reach was declared. Often more than one stream reach along a specific stream was surveyed. Since downstream reaches were generally larger than upstream reaches, it was expected that in-reach effects were greater than upstream influences. Therefore the reaches were treated as independent of one another.

3.2 DATA COLLECTION

Three types of data were collected in this study:

1. Predictor variables that may provide criteria to determine the likelihood of woody debris transport in the channel, or whether other negative effects may occur (Section 3.2.1).
2. Response variables that measured the extent to which the logging slash affected the channel morphology within that specific stream reach (Section 3.2.2).
3. Informative variables that provided additional information that did not fit into predictor or response categories. This category of data was not analysed, but was occasionally used to clarify conditions noted in the channel (Section 3.2.3).

3.2.1 PREDICTOR VARIABLES

Data for several predictor variables were collected. Many of the measurement procedures followed, or were similar to, those specified in the Channel Assessment Procedure Field Guidebook (Anonymous, 1996).

- Location: choices were open slope, *broadly incised*, gully, fan, valley flat, and canyon. *Broadly incised streams were similar to gullies, but channel gradients were less steep than gully channel gradients, the sidewalls were not as steep as gully sidewalls, and the sidewalls are not directly connected to the channel.*
- Average channel gradient, measured with a clinometer over most of the reach length (measured in degrees)
- *Maximum and minimum gradients (degrees)*
- Bankfull width (in metres, m)
- Bankfull maximum depth, measured from the thalweg to the top of the bank at the same location as width (m)
- *Bankfull average depth, an estimated average depth across the width of the channel (m)*
- Bankfull maximum area (the product of bankfull width and bankfull maximum depth, m^2)
- *Bankfull average area (the product of bankfull width and average depth, m^2)*
- Largest size of sediment moved ("sediment size moved", mm)
- Surficial material type/landform, grouped into colluvial and fluvial fans, fluvial plains, thick tills, till veneers, and rock dominated.
- *Channel bed type, grouped into:*

1) Boulder, cobble, or bedrock dominated
2) Pebble dominated
3) Sand or vegetation dominated. Vegetated channel beds had live vegetation growing on the bed such that the bed sediment was obscured.

- *Channel bank type, grouped into:*

1. Boulder, cobble, or bedrock dominated
2. Pebble dominated
3. Sand or vegetation dominated. Vegetated channel banks had live vegetation growing on the banks such that the bank sediment was obscured.

- For gullies, sidewall distance (m), sidewall gradient (degrees), gully bottom width (m), and confinement, defined as channel width/gully bottom width.
- *Road influence. If a road crossed the channel either within the study reach, or upstream of the channel reach, the study reach was deemed to have road influence.*

3.2.2 RESPONSE VARIABLES

In this study, several specific response variables that measured or estimated a specific stream characteristic were used to characterize how the study streams responded to logging slash. In addition, an overall disturbance variable was used to integrate the effects of the specific response variables. Data for the following response variables were collected:

- *Largest size of woody debris moved, grouped into four categories.*

1) Logs: >0.5 m diameter and >3 m in length, or >0.3 m diameter and > 5m in length.
2) Large woody debris (LWD): >0.1 m in diameter and >3 m in length, *or >0.3 m in diameter and >1 m in length.*
3) Small woody debris (SWD): anything smaller than LWD, *except twigs.*
4) *Twigs: <0.03 m in diameter and less than 1 m long.*

- The dimensions of individual woody debris jams were measured, and then the average jam volume (m^3) *and the average jam volume per length of channel (the "normalized jam volume", m^3/m) were calculated.*
- The dimensions of individual sediment wedges were measured, and then the average sediment wedge volume (m^3) *and the average sediment wedge volume per length of channel (the "normalised sediment wedge volume", m^3/m) were calculated.*
- Bed and bank erosion volumes, estimated with length, width, and depth estimates where recent erosion was apparent. *Bed and bank erosion were normalized by reach length (m^3/m).*
- Overall disturbance assessment, classified as:
    1) No disturbance
    2) Little disturbance
    3) Moderate disturbance
    4) Extensive disturbance, or
    5) Severe disturbance.

Overall disturbance was determined after recording all the other stream data, and was based on the presence and degree of one or more of the specific response variables. There were no predetermined criteria that equated set levels of specific responses to a specific overall disturbance level, and in addition, there was no requirement that any specific response must be part of the overall disturbance assessment.

3.2.3 INFORMATIVE VARIABLES

These variables either did not fit into the predictor or response variable categories, or were not used in formal analysis. In some cases they were used to clarify the causes of disturbance in the channel. As an example, stream reaches that were supplied with large amounts of sediment from slope failures may develop larger sediment wedges than channels not influenced by slope failures. Information on the following attributes was collected:

- Percent of channel covered by logging debris. This may have been affected by the original amount of logging debris deposited in the channel as well as whether the channel had transported the debris out of the channel.
- Percent of the logging debris in the channel that is composed of *twigs*, SWD, LWD, and logs, visually estimated.
- Percent of logging debris moving, visually estimated. Logging debris that had moved tended to be clustered against larger pieces, and was often aligned across the channel. In contrast, logging debris that had not moved was usually randomly orientated and not clustered.
- Percent of logging debris that was in jams, visually estimated.
- Dimensions of slope failures affecting the channel. The effect of the slope failure on the channel was noted. If the slope failure initiated a debris flow, the reach was not included in the study (however, none of these were found in the Anderson study area streams).
- Size of sediment supplied to the study reach by upstream sources, noted as sand, pebbles, cobbles, or boulders.
- Deposition sites other than sediment wedges, noted as in-channel, pool filling, or overbank deposition.

4.0 RESULTS

Forty-one stream reaches that met the criteria listed in 3.1 were surveyed. One of these 41 streams was excluded from further analysis since it appeared to have been significantly affected by skidder crossings. A few other streams appeared to have some effects resulting from skidder operations or cattle, but these

Figure 2. Average gradient

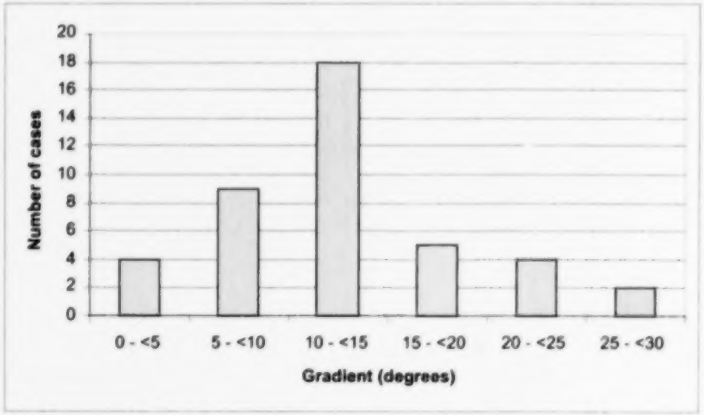


Photo 1

Stream 12 Reach 4 Overall disturbance: None	
Width (m)	1.5
Average Depth (m)	0.17
Gradient (degrees)	14
Sediment size moved (mm)	100
Size of logging debris moved	SWD
Mean logging debris jam size (m^3)	0.18
Normalised debris jam volume (m^3/m)	0.007
Mean sediment wedge size (m^3)	0.00
Comments: Mostly random alignment of logging slash indicates very little movement of woody debris. LWD prevents transport of twigs or SWD further than 1 or 2 metres.	

Photo 2

Stream 17 Reach 1 Overall disturbance: Extensive			
Width (m)	3.3	Size of logging debris moved	LWD
Average Depth (m)	0.31	Mean logging debris jam size (m^3)	0.64
Gradient (degrees)	11	Normalised debris jam volume (m^3/m)	0.808
Sediment size moved (mm)	220	Mean sediment wedge size (m^3)	0.77
Comments: Mostly SWD transported into small jams, with jams located every few metres. Overall disturbance for this channel is greater than is shown in this photo.			

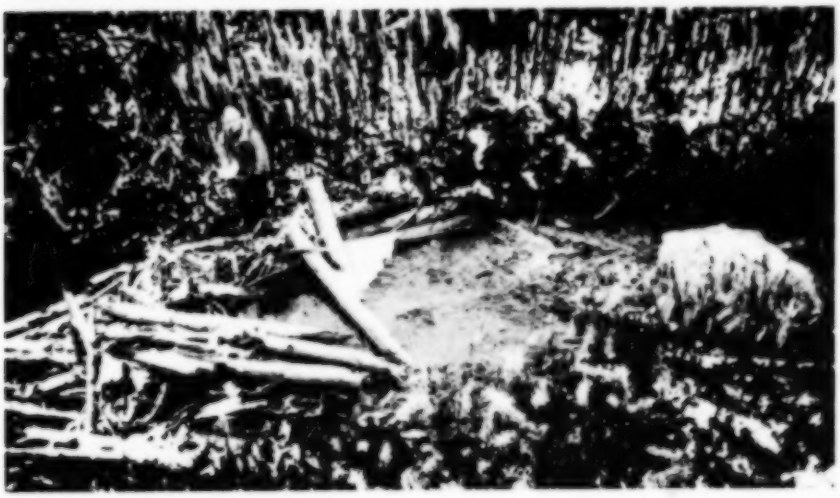


Photo 3

Stream 20 Reach 5		Overall disturbance	Moderate
Width (m)	2.6	Size of logging debris moved	LWD
Average Depth (m)	0.25	Mean logging debris jam size (m^3)	0.54
Gradient (degrees)	10	Normalized debris jam volume (m^3/m)	0.0643
Sediment size moved (mm)	200	Mean sediment wedge size (m^3)	0.57
Comments: Development of moderate sized jam containing LWD. Jams of this size usually incorporate logging slash derived from several metres of channel length.			

Photo 4

Stream 25 Reach 1		Overall disturbance	Severe
Width (m)	4.9	Size of logging debris moved	Logs
Average Depth (m)	0.28	Mean logging debris jam size (m^3)	6.9
Gradient (degrees)	4	Normalized debris jam volume (m^3/m)	0.16
Sediment size moved (mm)	340	Mean sediment wedge size (m^3)	6.9
Comments: Photo shows the largest jam recorded – 35 m^3.			

Figure 3. Stream location

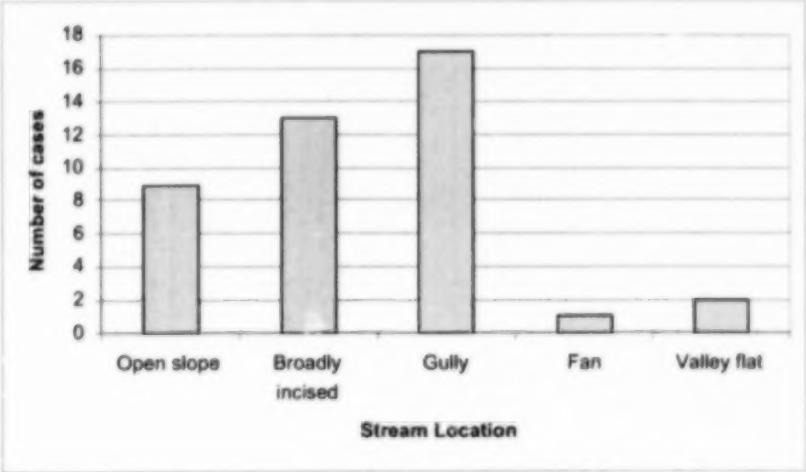


Figure 4. Terrain/landform types

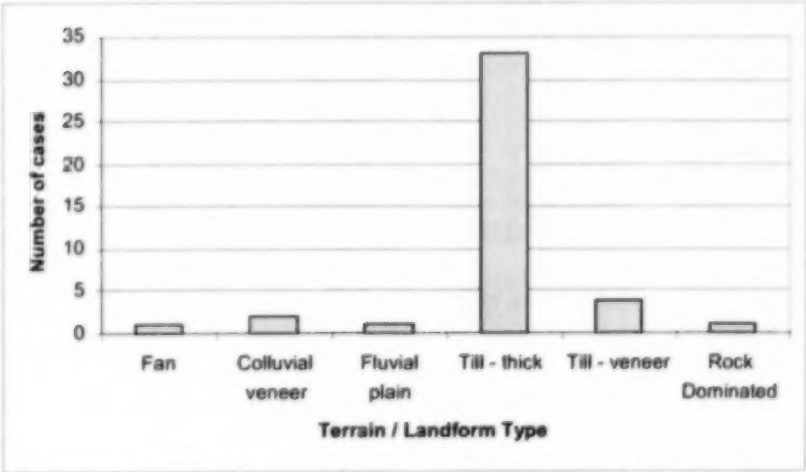


Figure 5. Bank types

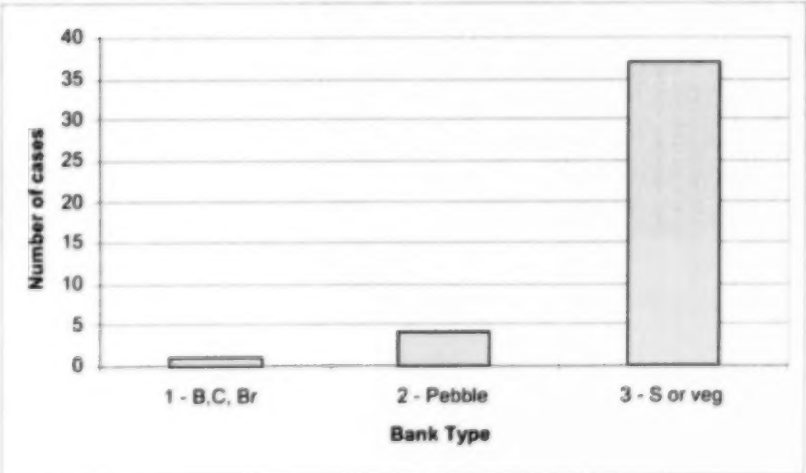
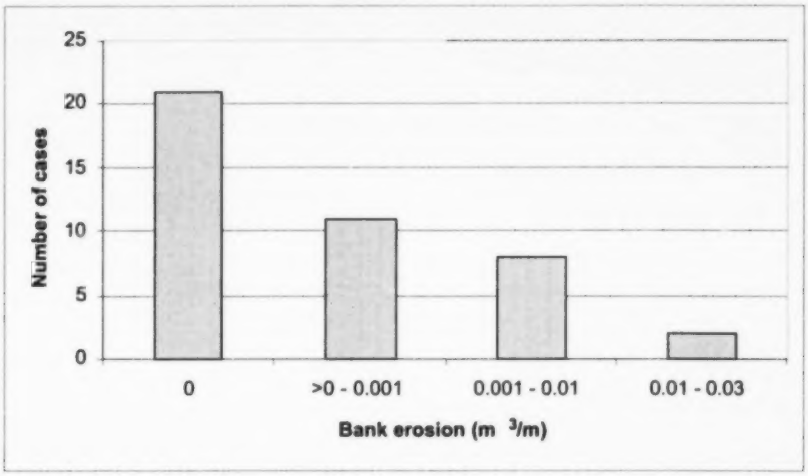


Figure 6. Normalized bank erosion



streams were included since the effects of the skidder operations or cattle generally seemed to not affect the overall response of the channel to the presence of logging slash. The streams were logged from 1986 to 1993, with two additional study reaches logged in 1997. These two additional reaches were included in the analysis for a total of 42 study reaches.

Stream reaches ranged from 32 to 295 m in length, with a median of 84 m. In terms of bankfull widths, surveyed reaches ranged in length from 20 bankfull widths long to 260 bankfull widths, with a median of 42 bankfull widths. Channel width ranged from 1.1 – 4.9 m, with a median of 1.9 m. Stream widths and depths were measured an average of 5.1 times, with a range of 3 to 7 times. Gradient ranged from 1 – 29° (2 – 55%), with a median of 12° (21%) (Figure 2).

Stream location is shown in Figure 3. Most streams were located on open slopes, or else were broadly incised or in gullies. Almost all streams were located on thick till terrain (Figure 4), with the remainder of the streams distributed in a variety of terrain types. Since the majority of the streams were located on thick tills, the variable terrain/landform type was excluded from further analysis. Similarly, most stream banks were predominantly sand or vegetation dominated (Type 3, Figure 5), and therefore the variable bank type was also excluded from further analysis.

Bed erosion in the study channels was rare, with only four of the 42 channels having any bed erosion. The maximum bed erosion was 0.008 m^3/m, and the other three channels had less than 0.002 m^3/m of bed erosion.

Bank erosion was more common. Half of the channels had some level of bank erosion. Figure 6 shows the distribution of bank erosion. The few channels located on terrain types other than thick till had some erosion, but only the thick till channels had bank erosion >0.002 m^3/m. The worst incidence of bank erosion was at a skid trail crossing. None of the other variables appeared to be associated with bank erosion.

4.1 SELECTION OF PREDICTOR VARIABLES FOR MULTIVARIATE ANALYSIS

Several of the predictor variables were correlated with other predictor variables. Only one predictor variable from a group of correlated predictor variables was needed for the multivariate analysis. Pearson correlation coefficients were determined for all pairs of continuous predictor variables, and criteria of an estimated $\rho = 0.50$ was used to identify correlated variables. For each group of correlated variables, one variable was selected. The specific variable chosen was based primarily on the basis of correlation with the response variables, but was also based on ease of use.

- Channel width and depth were correlated with each other. The product of width and depth (area, either maximum area or average area) was also used as a measure of channel size. Width was chosen as the best of these variables to use, since it was best correlated with the response variables, and is an easy-to-measure parameter.
- Sediment size moved was also correlated with the channel dimensions of width and depth. However, since sediment size moved is an easy-to-measure and a useful parameter, it was kept as a variable, and a second set of multivariate analysis variables was constructed.
- A Kruskal-Wallis test indicated that bed type was associated with channel size, with larger channels having beds dominated by larger sediment. Bed type was eliminated from multivariate analysis.
- Average gradient was chosen for multivariate analysis instead of minimum or maximum gradient. Average gradient was usually best correlated with the response variables.

The multivariate analysis of response variables used the following independent variables:

- Set 1: width, average gradient, location, and road influence.

Table 5. Comparison of channel width and the size of woody debris moved.

Size	# of cases	Channel width (m)		
		25th quantile[1]	Median	75th quantile
Twigs	4	1.1	1.3	1.4
SWD	23	1.5	1.6	1.9
LWD	14	2.3	2.8	3.1
Logs	1		4.9	

[1]At the 25th quantile, 25% of the study reaches have a channel width less than the stated value.

Table 6. Comparison of sediment size moved and the size of woody debris moved.

Size	# of cases	Sediment size moved (mm)		
		25th quantile	Median	75th quantile
Twigs	4	14	75	114
SWD	23	74	100	140
LWD	14	160	200	228
Logs	1		340	

- Set 2: sediment size moved, average gradient, location, and road influence.

For all statistical tests a significance level of 0.05 was used. Multiple regression models were determined using forward selection. To determine whether the model fit the data well, three tests were applied:

1. The distribution of the residuals was examined to determine whether it followed a normal distribution.
2. The residuals were plotted against the predicted values to determine whether the residuals exhibited heteroscedacity or if they indicated a transformation was needed.
3. The predicted values were plotted against the actual values to determine whether a 1:1 relationship existed.

If all of these conditions were met, then the statistical model fit the data well, and use of the model is justified. If the model strongly violated these conditions, the results were not reported.

4.2 LOGGING SLASH MOVEMENT AND JAM DEVELOPMENT

Three response variables were used to characterise the movement of slash in streams:

- The size of woody debris moved (Section 4.2.1).
- The average size of debris jams (Section 4.2.2)
- The normalized volume of woody debris in jams (Section 4.2.3).

4.2.1 SIZE OF WOODY DEBRIS MOVED

A Kruskal-Wallis test showed that width and the size of sediment moved were the only predictor variables to have significantly affected the size of woody debris moved. Tables 5 and 6 show the results. As channel width increased, so too did the size of woody debris transported. Similarly, as the size of sediment moved increased, so too did the size of woody debris moved. For both channel width and sediment size moved the Kruskal-Wallis test remains significant if the single case of logs being transported is excluded.

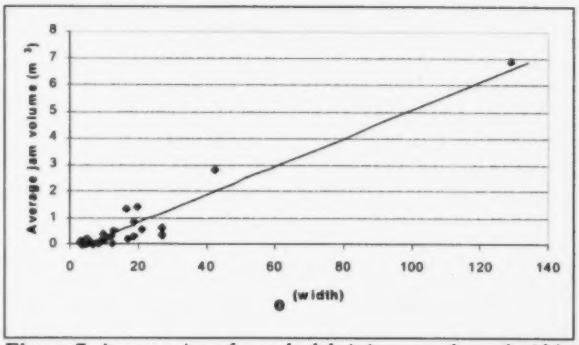


Figure 7. Average size of woody debris jams vs. channel width.

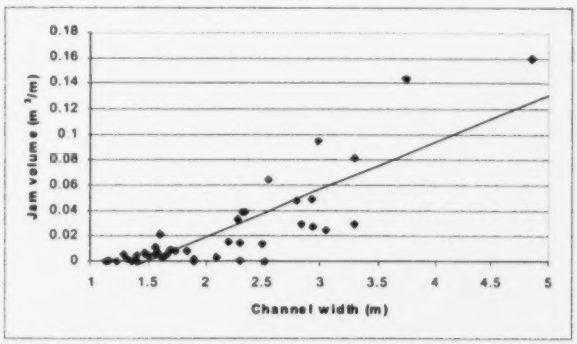


Figure 8. The effect of width on normalized debris jam volume.

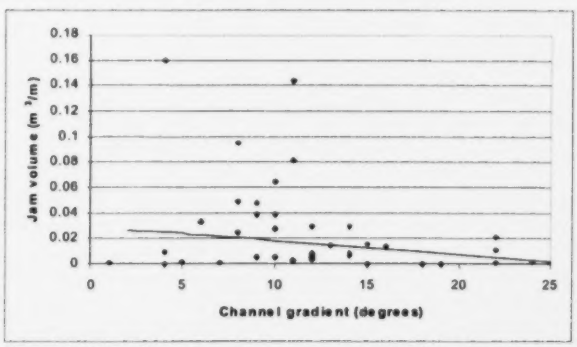


Figure 9. The effect of gradient on normalized debris jam volume.

4.2.2 AVERAGE SIZE OF DEBRIS JAMS

Multiple regression was used to determine whether Set 1 of the predictor variables (width, gradient, location, and road influence) had an effect on the average size of woody debris jams. The analysis showed only width was significant. A transformation using the exponential of width yielded the best result, as shown in Figure 7 and Equation 1. Although Equation 1 would appear

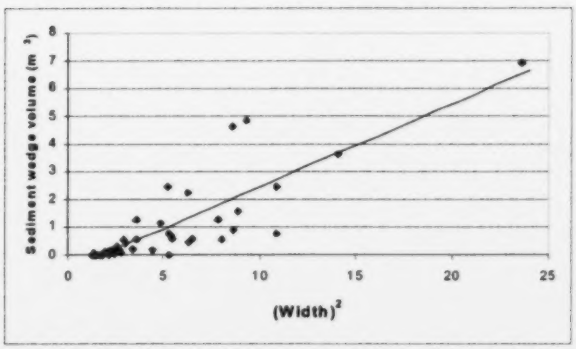


Figure 10. The effect of width on average sediment wedge volume

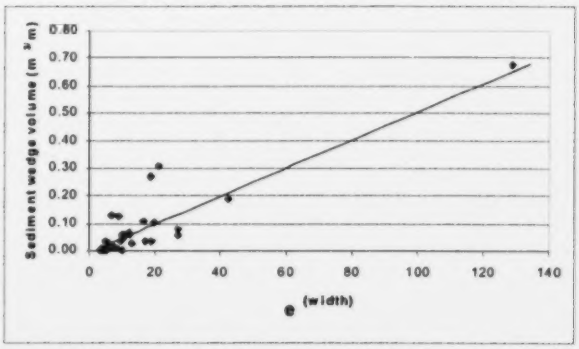


Figure 11. The effect of width on normalized sediment wedge volume.

to be strongly influenced by the outermost data point, a regression excluding this data point yielded an almost identical equation.

Equation 1. Average jam size = $-0.24 + 0.053e^{(width)}$
$R^2 = 0.94$, n = 42.

4.2.3 NORMALIZED DEBRIS JAM VOLUME

Multiple regression was used with Set 1 of the predictor variables to determine whether they affected the normalized debris jam volume. The test indicated that both width and average gradient were significant, as shown in Equation 2. Figures 8 and 9 show how width and channel gradient affected normalized jam volume. For Figure 8, the regression line was calculated with a constant channel gradient of 12° (21%). For Figure 9 the regression line was calculated with a constant channel width of 1.9 m.

Equation 2. Normalized jam volume =
$-0.041 - 0.0011$(gradient) $+ 0.037$(width)
$R^2 = 0.74$, n= 42.

Set 2 of the predictor variables did not yield a statistically valid model of normalized debris jam volume, although sediment size moved was found to be significant.

4.3. SEDIMENT WEDGE DEVELOPMENT

4.3.1 AVERAGE SEDIMENT WEDGE VOLUME

Multiple regression was used to test the Set 1 predictor variables against the average sediment wedge volume. Only width was significant. Figure 10 shows the relationship between width and average sediment wedge volume. The best fit is described by Equation 3. The residuals were not normally distributed and displayed some heteroscedasticity, so this result should be treated somewhat cautiously.

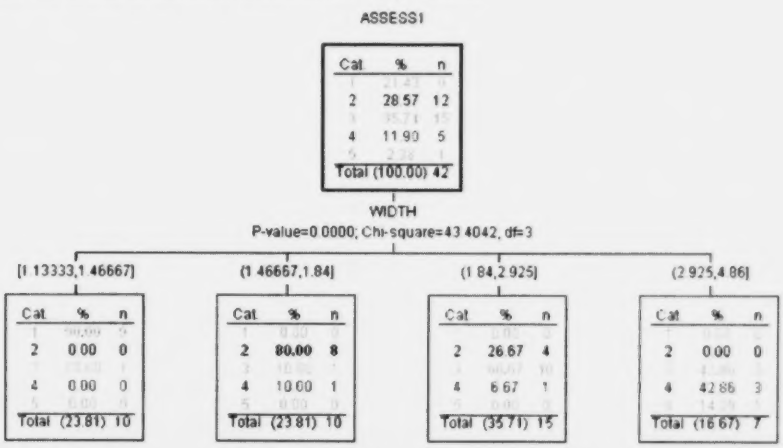
Equation 3. Average sediment wedge volume = $-0.56 + 0.30(\text{width})^2$
$R^2 = 0.70$, n = 42

Set 2 of the predictor variables did not yield a statistically valid model of sediment wedge volume, although both sediment size moved and gradient were found to be significant.

4.3.2 NORMALIZED SEDIMENT WEDGE VOLUME

The average volume of sediment wedges per channel length was also considered. As before, only width was a significant in-

Figure 12. CHAID tree for overall disturbance in Anderson study streams



dependent variable. Figure 11 shows the best fit regression of normalized sediment wedge volume vs. width. The model did not fit the data well, and therefore the results should be used cautiously. Excluding the outermost data point yields a similar regression line.

Equation 4. Normalized sediment wedge volume = $-0.0059 + 0.0051e^{(width)}$

$R^2 = 0.80$, n = 42

Set 2 of the predictor variables did not yield a statistically valid model of normalized sediment wedge volume, although sediment size moved was found to be significant.

4.4 ANALYSIS OF OVERALL DISTURBANCE

TR-005 used CHAID (Chi-Square Automatic Interaction Detection) to analyse overall disturbance. CHAID is a segmentation analysis procedure that divides the sample population into two or more groups based on the best predictor. Each subgroup may be divided further using the next best predictor. All variables are treated as categorical variables, and continuous variables will be automatically grouped according to the most significant results (Anonymous, 1998). The CHAID analysis of overall disturbance for the Anderson study area data is shown in Figure 12. In Figure 12, Category 1 is No Disturbance, and Category 5 is Severe Disturbance (Section 3.2.2). CHAID selected width as a significant predictor of overall assessment. CHAID identifies four classes of stream width, and as stream width increases, the modal disturbance class increases as well. No other variables were selected as significant.

5.0 DISCUSSION

Both this study and TR-005 show that the movement of logging slash in S5 and S6 channels is a predictable quantity. Logging slash, and woody debris in general, will be transported if the transport capability of the stream is greater than the resistance of the woody debris to water transport. The resistance of woody debris to movement is likely a combination of the size of individual pieces, how an individual piece interacts with other woody debris pieces, and woody debris interaction with the channel bed and banks.

Woody debris transport capability of a stream is primarily a function of the channel size. In this project (both TR-005 and this report), channel size was measured using bankfull width and maximum depth, and calculated a maximum cross-section area using these measurements. In addition, this report also measured average cross-section depth, and calculated an average cross-section area. The results from both project phases shows that channel width was the best measure of channel size for predicting logging slash transport.

As channel width increased, so too did the size of woody debris transported (Table 5), the size of woody debris jams (Figures 7 and 8), and the size of sediment wedges (Figure 10). Both increased size of woody debris transported, and increased debris jam volume, indicate an overall greater transport of woody debris. In the smallest channels in these studies, logging slash was usually randomly distributed, and only a few pieces of the smallest size appeared to have moved (Photo 1). As channel width increased, a greater percentage of the logging slash moved, and the piece size moved also increased (Photo 2). However in most cases some obstruction in the channel – often a larger piece of wood – caused the slash to stop moving. These locations developed into debris jams. For still larger channels, the stream was capable of transporting pieces of wood that could act as an obstruction in a smaller channel. As a result, debris jams tended to be spaced further apart, but were of greater size (Photo 3). The largest stream surveyed in the Anderson study, at 4.9m wide, had almost no wood in most of the reach length. Almost all the wood that was retained in the reach was in one jam that was approximately 35 m^3 in size (Photo 4), and it is likely that significant amounts of woody debris were transported out of the reach.

Since most woody debris jams occupy the width of the channel, there may be some degree of spurious correlation between channel width and the size of woody debris jams. Other measures of woody debris jams were tested as well to avoid the possibility of a spurious correlation with channel width. These measures were debris jam volume normalised by channel area (reach length and bankfull width), and debris jam volume normalised by channel volume (reach length, bankfull width, and average depth). Both of these measures showed width to be the most significant variable affecting them. The significance of width to these measures of woody debris jam volume indicates that width has more than just spurious correlation.

Stream gradient was shown to be significant in affecting jam volume (Section 4.2.3, Figure 8). For channels of a given size, lower gradient channels developed larger jams. This suggests that lower gradient channels are more efficient at transporting woody debris. The most reasonable explanation for this result is that lower gradient channels have less form and grain roughness (Knighton, 1984), and therefore woody debris is less likely to encounter resistance to movement.

The size of sediment moved significantly affected the size of woody debris transported (Table 6). In addition, the size of sediment moved significantly affected the size of woody debris jams and the size of sediment wedges, but statistical models did not fit the data well, and were therefore not reported. The size of sediment transported in a stream is an indication of the stream's transport capability, and can be used to predict the movement of logging slash. However, it appears that the relationship between woody debris movement and sediment movement is confounded by additional factors that were not determined in this study. It may be that the size of sediment in a stream may not actually reflect the true transport capability, or woody debris and sediment are not responding to the same transport processes. As noted above, gradient is inversely related to normalised debris jam volumes, and this indicates that lower gradient channels are more capable of transporting logging debris. In contrast, the size of sediment transported is positively related to gradient (Knighton, 1984).

In general, the development of sediment wedges was predicted by the same variables as was woody debris transport and debris jam development. However, the relationships were not as statis-

Table 7. Assessment of water transport potential

Water transport potential	Low	Moderate	High
Bankfull channel width (m)	≤ 2	> 2 - ≤ 3.5	> 3.5
Size of water transported woody debris	SWD	LWD	Logs
Largest sediment transported (mm)	≤ 100	> 100 - ≤ 200	> 200

Logs: > 0.5m diameter and > 3m long, or > 0.3m diameter and > 5 m long.
Large woody debris (LWD): >0. 1m diameter and >3 m in length, or > 0.2 m diameter and >1 m in length, up to the size of logs.

Table 8. Recommended cleaning strategies

Water transport potential	Cleaning strategy
Low	Do not clean
Moderate	Clean all introduced SWD and most LWD
High	Clean all logging debris except larger logs

tically robust. Sediment wedge development may have been restricted by sediment supply, whereas these logged streams probably were not woody debris supply-restricted. This may have caused the greater variability in sediment wedge relationships.

Half the channels in this study had some degree of bank erosion, compared with one-third of the channels in the Nitinat area (TR-005 study). In both studies the amount of erosion tended to be minor. Of those channels with bank erosion, most had less than 0.001 m^3/m of bank erosion. Although there was apparently a greater frequency of bank erosion in this study, a Kruskal-Wallis test indicated there was no significant difference in the amount of bank erosion that occurred between the Nitinat study area streams and the Anderson study area streams. The finer grained sediments in the Anderson River study area did not experience more erosion than streams in the Nitinat area. Overall, logging slash rarely caused significant bank erosion. However, specific cases were noted where individual pieces of logging debris or debris jams diverted all or a portion of the flow out of the stream channel, causing a significant amount of erosion.

6.0 CONCLUSION

Results of this study confirm the results of the TR-005 study. In both studies, channel width and the size of sediment moved were the most useful predictor variables. In both studies, streams that were less than 2 m wide, or that had sediment less than 100 mm in size transported, tended to have low levels of channel disturbance or development of woody debris jams or sediment wedges. Although the study results are very similar, the terrain, biogeoclimatic zones, and peak flow hydrologic processes are considerably different between the two study areas. Therefore it is likely that these studies typify channel response to the presence of logging debris in the Vancouver Forest Region.

Tables 7 and 8 are reprinted unchanged from TR-005, and contain an assessment procedure and recommendations for stream cleaning. Most of the channels assessed for this study were open slope, broadly incised, or gullied channels. This is similar to TR-005, where most of the channels were open slope or gullied channels. Caution is urged when applying these results to valley flat or fan channels because few valley flat or fan channels were sampled. As stated in TR-005, the recommended procedure is to calibrate these results with local examples.

In Table 7, if one or more criteria are evaluated as high, then the overall water transport assessment is high. If there are no criteria ranked as high, then one or more moderate evaluations results in an overall water transport potential as moderate.

7.0 REFERENCES

Anonymous. 1998. *Answer Tree 2.0 Users Guide.* SPSS Inc. Chicago, USA. 209p.

Anonymous, 1996. *Channel Assessment Procedure.* Ministry of Forests and B.C. Environment, Victoria, B.C. 95p.

Commandeur, P., B. Guy and H. Hamilton. 1996. *The effects of woody debris on sediment fluxes in small coastal stream channels.* Canadian Forest Service, Victoria, B.C. 27 p.

Green, R.N. and K. Klinka. 1994. *A Field Guide to Site Identification and Interpretation for the Vancouver Forest Region.* Province of British Columbia, Victoria, B.C. 285 p.

Holland, S. 1976. *Landforms of British Columbia.* British Columbia Department of Mines and Petroleum Resources, Bulletin 48. 138 p.

Hudson, R. 2000. *Assessing Snowpack Recovery of Watersheds in the Vancouver Forest Region.* Vancouver Forest Region Technical Report TR-004. Nanaimo, B.C. 34 p.

Knighton, D. 1984. *Fluvial Forms and Processes.* Edward Arnold, London, U.K 218p.

Millard, T. 2000. *Channel Disturbance and Logging Slash in S5 and S6 Streams.* Vancouver Forest Region Technical Report TR-005. Nanaimo, B.C. 20 p.

Monger, J. 1969. Hope (West Half) Geology Map 12-1969. Geological Survey of Canada.

Waddington, B.A. 1995. *The Fraser Glaciation in the Cascade Mountains, Southwestern British Columbia.* Unpublished M.Sc. thesis, Department of Geography, University of British Columbia. Vancouver, B.C. 161 p.